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Natural Resource Stewardship and Science

Management of Plains Cottonwood at Theodore Roosevelt National Park, North Dakota

Natural Resource Report NPS/THRO/NRR—2017/1395

ON THIS PAGE
Flooded cottonwoods and buildings, North Unit Campground, Theodore Roosevelt National Park, May 26, 2011.
Photograph by Theodore Roosevelt National Park Staff.

ON THE COVER
Bison, calf and cottonwood forest, Little Missouri River in Theodore Roosevelt National Park, April 15, 2004.
Photograph by Jeff Hughes (National Park Service).

Management of Plains Cottonwood at Theodore Roosevelt National Park, North Dakota

Natural Resource Report NPS/THRO/NRR—2017/1395

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Executive Summary

Establishment of cottonwood trees is driven by flood-induced channel migration, which provides the new surfaces necessary for successful germination and survival. Along the Little Missouri River the largest floods typically result from snowmelt in March or April. Seed release occurs in early summer, and seedlings usually germinate in moist, open locations on point bars at relatively low elevations above the channel. Subsequent channel migration allows seedlings to mature by protecting them from scour in floods and ice jams. Management actions that decrease channel movement will reduce cottonwood reproduction.

Growth and survival of cottonwood trees are strongly decreased by extreme low flows. As a result, management activities that decrease low flows could strongly reduce growth or kill trees. Surface-flow diversions are less damaging to trees if carried out during the spring when flows are relatively high. Herbicide application by helicopter to control leafy spurge appears to have inadvertently damaged or killed about 25% of the cottonwood forest along the Little Missouri River in the South Unit. Area of adult trees sprayed has been reduced since 2007 to limit this damage. It is not known whether spraying of cottonwood seedlings on unforested point bars is reducing cottonwood reproduction in the South Unit.

Warmer temperatures since 1976 have reduced flood peaks and the ice jamming that magnifies those peaks; as a result channel movement, cottonwood establishment and cottonwood growth have decreased. Increasing temperatures associated with global climate change could continue this trend.

Acknowledgments

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Introduction

An outstanding feature of Theodore Roosevelt National Park (THRO) is the exceptionally old and undisturbed gallery forest of plains cottonwood (*Populus deltoides* subsp. *monilifera*) along the Little Missouri River. THRO protects the oldest known plains cottonwoods in the world, established as early as the year 1641 and growing up to 1.66 m (5.45 ft) in diameter. As the largest and most abundant tree in the riparian ecosystem, cottonwoods provide important habitat for many other species (Brinson et al. 1981). Cottonwood tree rings at THRO preserve a 300-year record of variation in flow and climate (Edmondson et al. 2014, Meko et al. 2015). The forest also directly relates to the history of the Park because it provided building sites and materials for the ranches of Theodore Roosevelt, as well as habitat for the game he hunted and forage and protection for his livestock. This report summarizes research conducted by the U.S. Geological Survey from 2003 through 2016 on factors controlling reproduction and survival of plains cottonwood at the North and South Units of THRO (Figure 1), and is relevant to management of cottonwood-dominated forests throughout the western United States. Details of methods and results are available in Miller and Friedman (2009), Edmondson et al. (2014), Meko et al. (2015), Schook et al. (2016) and Griffin and Friedman (2017).

Although cottonwood forests dominate river floodplains in dry regions of North America, Asia, Europe and Africa, naturally reproducing examples like the forest at THRO are increasingly rare. Most of the formerly vast floodplain forests of the upper Missouri River have been flooded and killed by reservoirs (Volke et al. 2015). Along most of the remaining rivers in the northern Great Plains, flood control by dams decreases the channel movement that provides opportunities for cottonwood reproduction (Johnson et al. 2012). Invasive trees, especially saltcedar (*Tamarix* spp.), Russian olive (*Elaeagnus angustifolia*), and Siberian elm (*Ulmus pumila*) are replacing much of the native forest (Friedman et al. 2005, Johnson et al. 2012). Floodplain stabilization and development have removed native forest and prevented channel movement necessary for cottonwood reproduction. In contrast, the Little Missouri River watershed contains no large reservoirs, and only moderate upstream withdrawals for irrigation (Griffin and Friedman 2017). Water management has not reduced peak flows or altered the seasonal pattern of flow variation (Griffin and Friedman 2017). Invasive Russian olive, saltcedar and Siberian elm are infrequent on the floodplain. Protection of the floodplain within the Park has minimized construction activities and cutting of cottonwoods. As a result, THRO contains one of the best remaining examples of a free-flowing plains river and associated naturally reproducing cottonwood forest. The Little Missouri River in THRO is the only riverine Federal Wilderness Area in North Dakota, a State Scenic River, and one of only 3 rivers in North Dakota classified by the NPS Nationwide Rivers Inventory as having "outstandingly remarkable" natural or cultural values.

THRO has been a center of research on cottonwood forests for over 50 years. Working at the North Unit, Everitt (1968) was the first to show that floodplain surfaces could be dated by aging the cottonwood trees growing upon them. He reported that cottonwood establishes in even-aged bands and that the different-aged bands track the gradual movement of the active river channel across the floodplain. This work served as a model for application of tree-ring science to studies of channel change around the world. Reily and Johnson (1982) used tree rings from the North Unit of THRO as a reference data set in a study of the effects of large reservoirs on growth of cottonwood along the Missouri River.

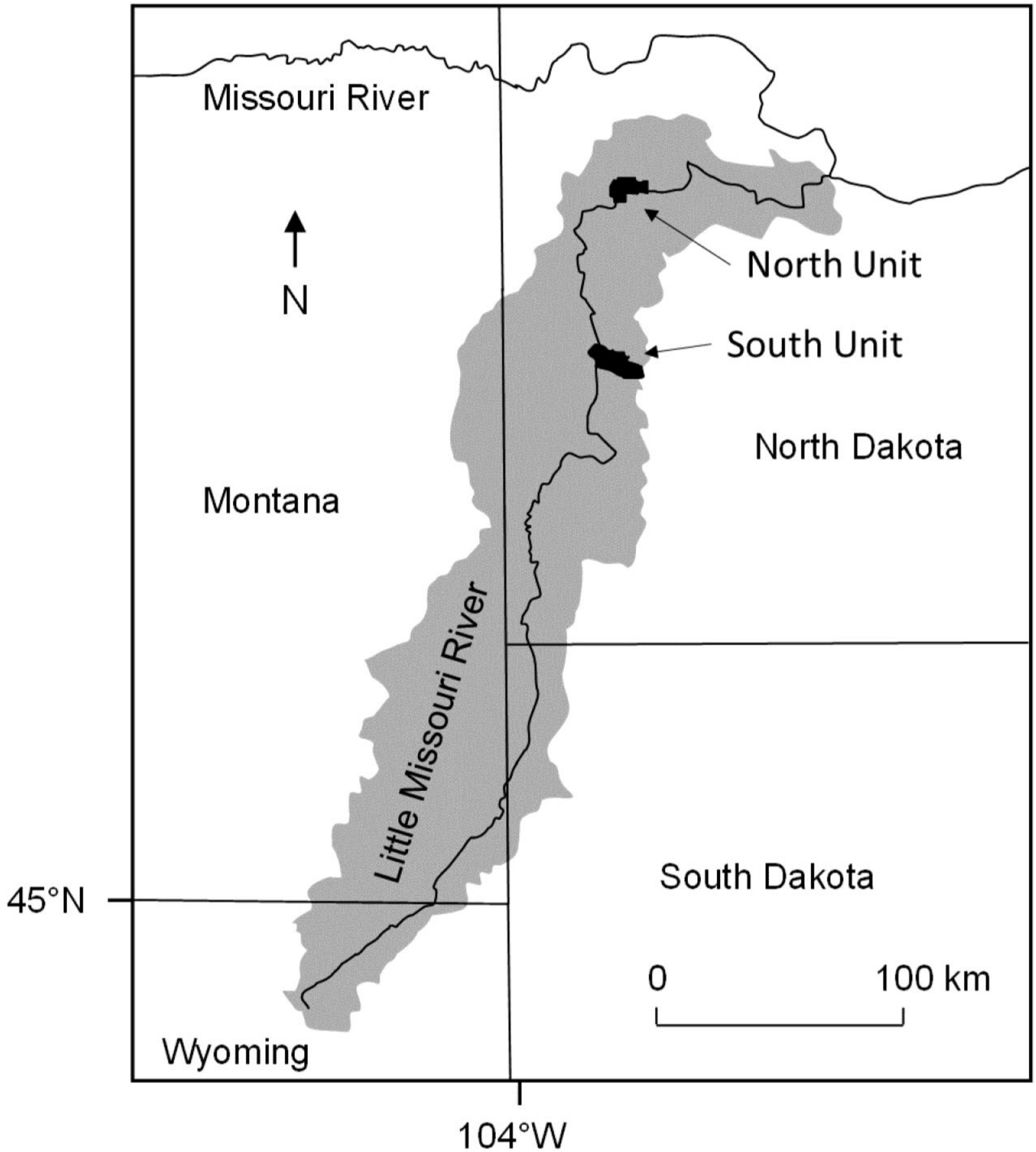

Figure 1. The North and South units (shaded black) of Theodore Roosevelt National Park along the Little Missouri River in North Dakota. The Little Missouri River watershed is shaded gray. Modified from Meko et al. (2015).

Gonzalez (2001) used rings of cottonwoods to date arroyo cutting and filling in badlands tributaries to the Little Missouri River in THRO. Miller and Friedman (2009) related flow variability to channel change and cottonwood establishment. Using cores from the North Unit, Edmondson et al. (2014) showed that cottonwood trees have distinct rings whose width is strongly correlated with precipitation. Meko et al. (2015) used those same cores to develop a reconstruction of flow in the Little Missouri River back to 1643. Their approach is now being replicated throughout the Upper Missouri River Basin (Schook et al. 2016). Griffin and Friedman (2017) demonstrated that a decline in flow since 1976 is related mostly to increasing temperatures. These studies have focused on the North Unit of THRO. The South and Elkhorn units have received less attention, perhaps because their forests are less extensive. In addition to summarizing our findings in the North Unit, this report extends analyses of cottonwood establishment and growth at THRO to the South Unit.

Flow and Climate

Peak flow along the lower Little Missouri River usually occurs as a result of snow melt (Griffin and Friedman 2017). Because the watershed contains no mountains, the snowmelt occurs early, in late March or early April (Figure 2). In contrast, larger northern Plains rivers like the Yellowstone often have peaks in May or June as a result of montane snowmelt (Schook et al. 2016). Flood peaks on the Little Missouri River are often magnified by formation and breakup of ice jams. The northward flow direction of the river accentuates ice jams because a large temperature gradient can exist between the southern upstream sections that typically melt early and the northern downstream sections that may remain ice-covered longer. Heavy spring and summer rains in the Little Missouri Basin also can produce high flows, which are sometimes larger than the spring peak. The river can cease to flow in the late summer of particularly dry years. Because mean monthly flow peaks in March or April, precipitation peaks in June, and temperature peaks in July and August (Figure 2), the floodplain environment becomes progressively drier over the growing season.

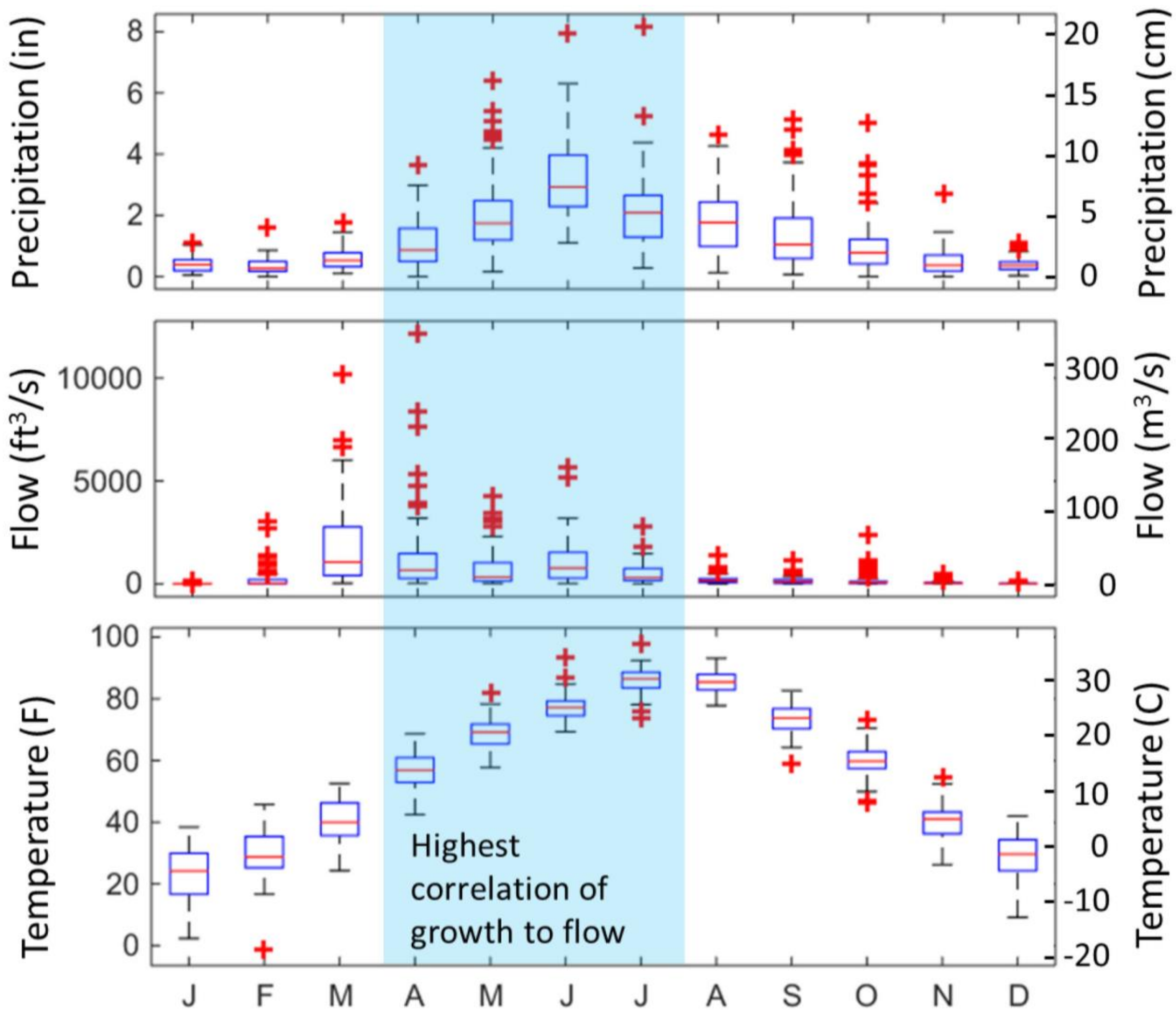

Figure 2. Distribution of monthly precipitation, mean flow and temperature 1931-2010, North Unit of Theodore Roosevelt National Park, ND. Output is from SEASCORR (Meko et al. 2011). Monthly temperature and precipitation data are from PRISM (Daly et al., 2008) for a point in the center of the cottonwood sampling area in the North Unit of THRO. Flow data are from gage 06337000 supplemented before 1935 by correlation with gage 06336000.

Species Composition of the Riparian Forest

The dominant tree species along the Little Missouri River in North Dakota include plains cottonwood, rocky mountain juniper (*Juniperus scopulorum*), green ash (*Fraxinus pennsylvanica*), and American elm (*Ulmus americana*). Sandbar willow (*Salix exigua*) is associated with young cottonwood along the active channel, and the ash, elm and juniper gradually become established within older cottonwood stands on the higher floodplain surfaces (Figure 3). Between these two zones, cottonwoods are typically found in pure stands (Johnson et al. 1976, Edmondson et al., 2014). This strong dominance of cottonwood over other trees is characteristic of riparian forests in the western Great Plains. In eastern North Dakota, more humid conditions allow development of broader riparian forests with higher cover of elm and ash and occurrence of other tree species including burr oak (*Quercus macrocarpa*) and common hackberry (*Celtis occidentalis*).

Figure 3. Cottonwood stands of different ages along the Little Missouri River in the North Unit of Theodore Roosevelt National Park, ND, (left) young trees roughly 15 years old near the active channel, (middle) mature cottonwoods roughly 50 years old with no other woody species, (right) the oldest known plains cottonwood in the world (370 years old) with understory of rocky mountain juniper and green ash. Photos taken by Jesse and Alan Edmondson in 2010. Modified from Edmondson et al. (2014).

Management

Cottonwood Establishment Depends Upon Channel Change Driven by Floods

Channel migration is brought about by erosion mostly along the outside of bends during the largest floods. These floods temporarily widen the channel, making room for later deposition of sand on the inside of bends (point-bars). At the North Unit, 91% of the decadal-scale variation in erosion rate is explained by peak flows (Figure 4) and more than 50% of sand transport occurs in flows exceeded on average about 1 day per year (Figure 4), but most floodplain formation occurs during decades of low flow, when vegetation is able to survive on point bars (Miller and Friedman 2009). The new vegetation traps sediment, raising the point bars to the elevation of the floodplain. Because erosion and deposition are distinct processes associated with distinct aspects of the flow regime, channel width fluctuates over time as the channel migrates like an inchworm across the floodplain (Nanson and Hickin 1983).

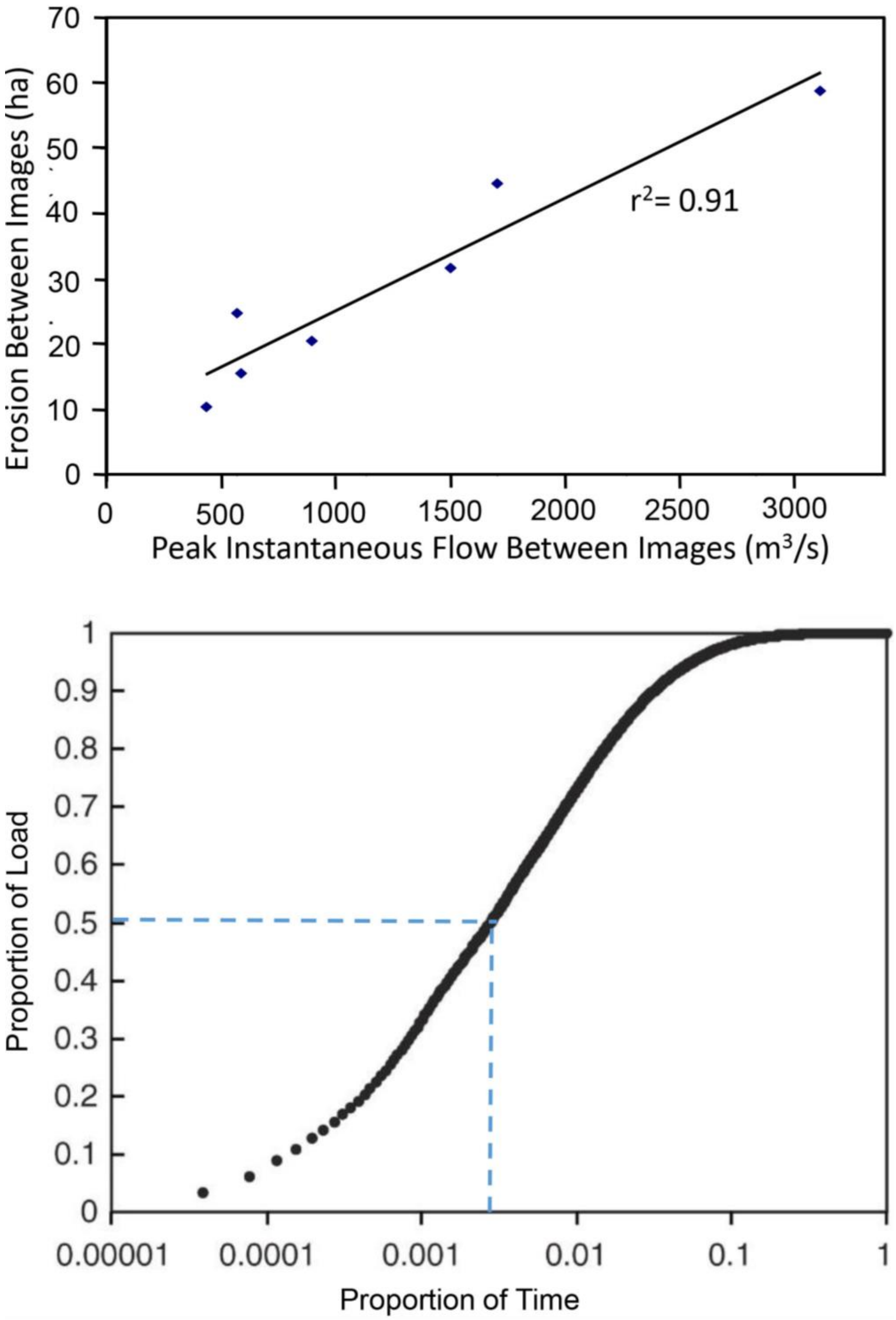

Figure 4. Relation between channel change and flow in the North Unit of Theodore Roosevelt National Park, Little Missouri River near Watford City, North Dakota (gage 6337000). Top, erosion in an interval between aerial images (8-13 yr) as a function of the peak instantaneous flow in the interval. Aerial images were captured in 1939, 1949, 1958, 1966, 1974, 1982, 1995, and 2003. Bottom, proportion of suspended sand load vs. flow exceedance. Dashed blue lines illustrate that 50% of the sand load is carried by flows exceeded on average about 1 day per year. Modified from Miller and Friedman (2009).

Cottonwood, willow and other riparian pioneer species have strict requirements for seedling germination and establishment that are rarely met in the dry landscape of the western Great Plains. Seedlings of these species require large amounts of light and moisture to survive. Typically these requirements are met only in locations disturbed and irrigated by the river (Scott et al. 1996). Seeds are dispersed large distances in high numbers but have no dormancy and must germinate within a few weeks of dispersal. Because seeds are released in June and July, long after snowmelt peaks of the Little Missouri River in March or April, seedling establishment at THRO occurs mostly low on point bars (Figure 5).

Figure 5. Cottonwood seedlings on a point bar along the Little Missouri River in the North Unit of THRO. Channel migration away from the point bar allows seedling establishment and erodes the opposite bank. Photo by Jeff Hughes, July 29, 2003.

Most seedlings are knocked over or killed by subsequent flows of water and ice (Figure 6) or by beavers, but migration of the river away from the point bars allows some seedlings to survive (Figure 7, Everitt 1968). Sediment deposition raises the surfaces occupied by seedlings, and eventually the young trees are far enough away and high enough above the channel to escape damage from high flows, floating ice and beavers (Figure 7). Progressive migration of the channel and sediment deposition produce a sequence of arc-shaped bands, increasing in age and elevation with distance from the channel (Figures 8 and 9). Cottonwood seedlings cannot survive in the dark, dry conditions under adult trees, resulting in roughly even-aged stands of trees whose age dates the formation of the underlying floodplain. As trees die, the local number of stems per hectare gradually declines (Figure 10). Although male cottonwoods are thought to be more tolerant of drought than females (Hultine et al. 2007), we did not find an increase in the proportion of males in older stands at THRO (Figure 11), and the overall percentage of male trees is close to 50% at both units (49.4% at the South Unit and 51.2% at the North Unit).

Figure 6. Ice in Little Missouri River, March 2004. Photo by Theodore Roosevelt NP Staff.

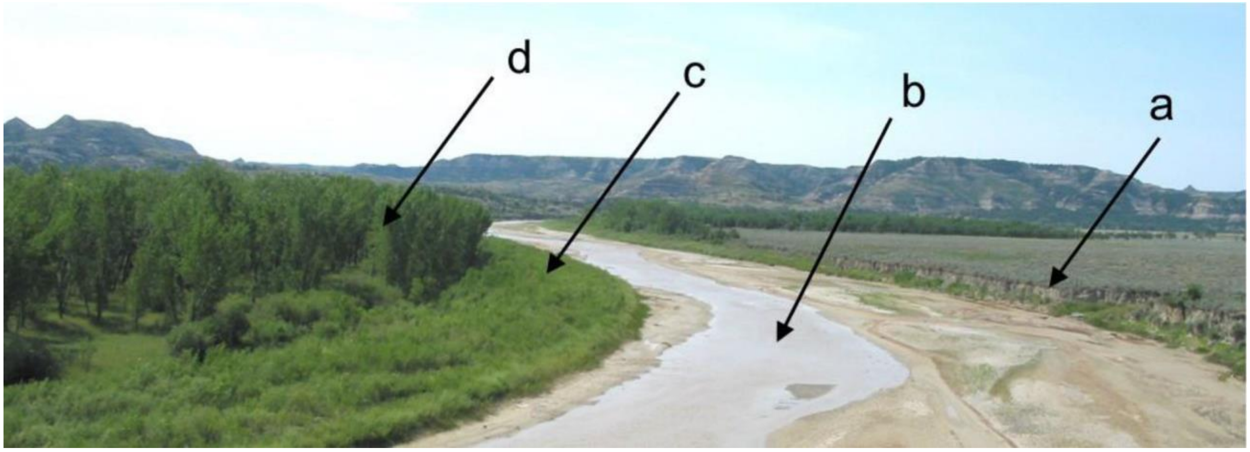

Figure 7. Little Missouri River in THRO, North Unit, showing (a) recently eroded cutbank on the outside of a bend, (b) the channel kept free of vegetation by frequent scouring flows, (c) a point bar with vegetation including cottonwoods frequently knocked over by ice or harvested by beaver, and (d) a low flood plain surface occupied by cottonwoods that have escaped frequent damage by ice and beaver. Flow is top to bottom and channel migration is left to right. Photo by Jeff Hughes, July 29, 2003.

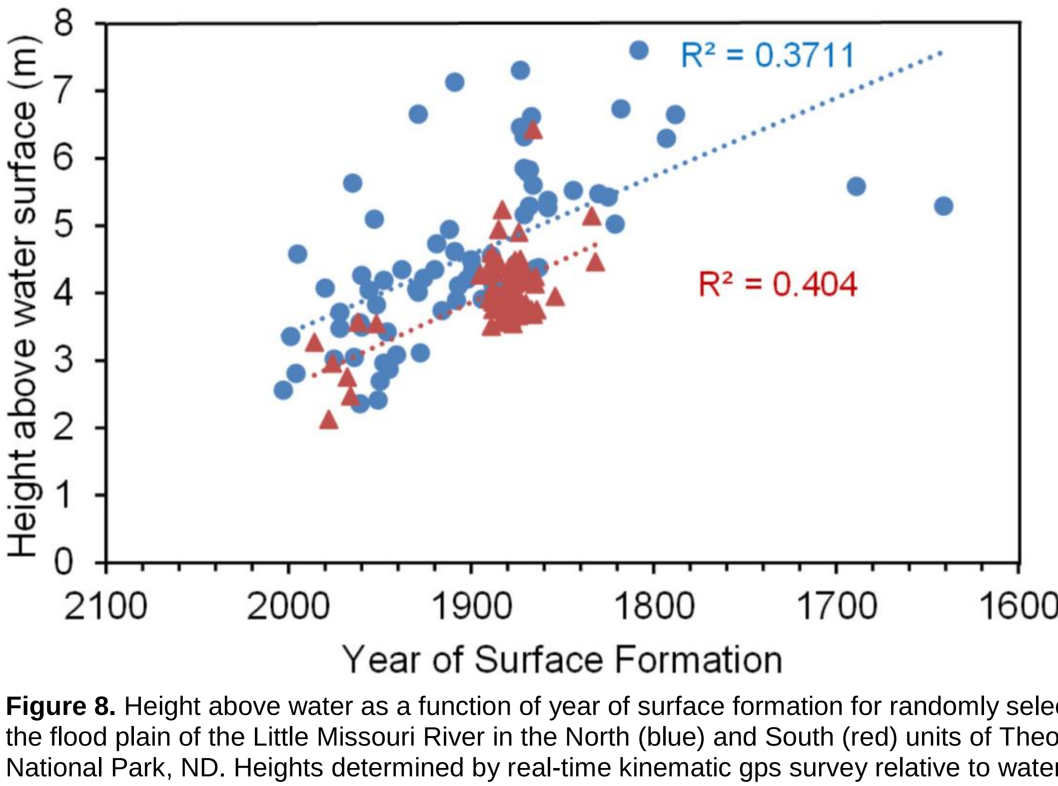

Figure 8. Height above water as a function of year of surface formation for randomly selected points on the flood plain of the Little Missouri River in the North (blue) and South (red) units of Theodore Roosevelt National Park, ND. Heights determined by real-time kinematic gps survey relative to water surface on April 17-20, 2012 at South Unit at flows of 2.2-2.5 m3/s (gage 06336000) and April 21-24, 2012 at North Unit at flows of 4.0-4.1 m3/s (gage 06337000). Year of surface formation estimated by ring count of the closest tree. Physically, the trendlines should become less steep on older surfaces, but there is insufficient data from trees established before 1760 to fit such a curve.

Figure 9. The Little Missouri River, flood plain and surrounding badlands in the North Unit of THRO. Leafless gray trees on the flood plain are mostly cottonwood, and dark green trees on the flood plain and badlands are rocky mountain juniper. Cottonwood stands occur in arc-shaped bands increasing in age with distance from the channel. Photo looking downstream by Jonathan Friedman, April 22, 2012.

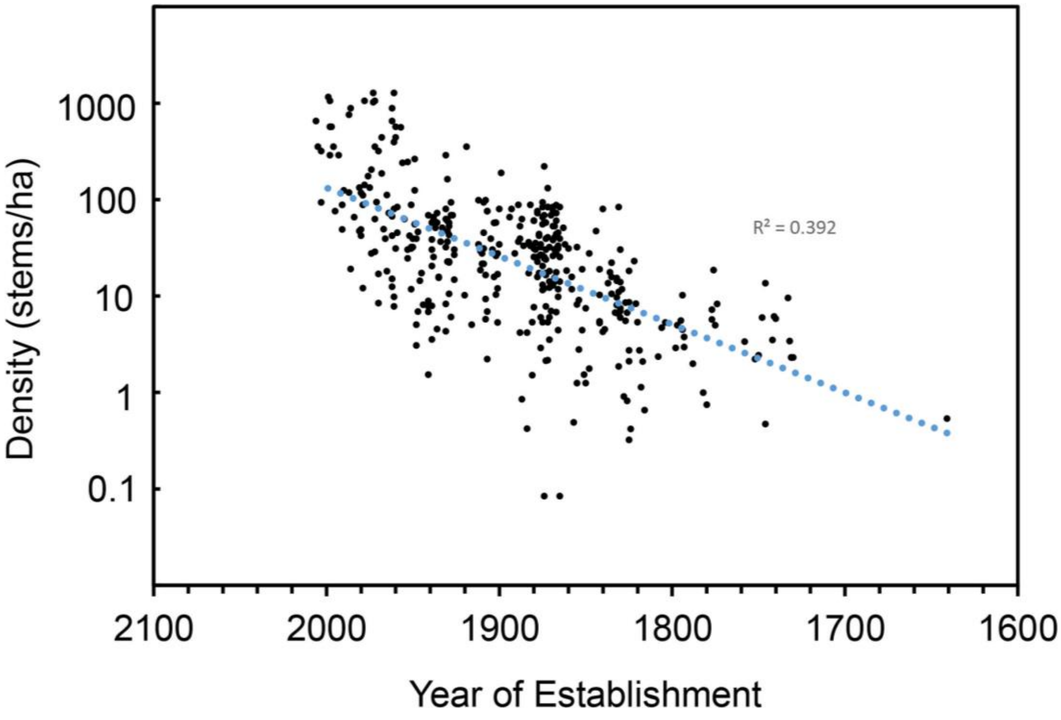

Figure 10. Stem density at random points in cottonwood stands in the North Unit of THRO as a function of year of establishment. Note exponential y axis. Stem density was estimated at random points by measuring the area containing the nearest 10 trees (Friedman and Lee 2002).

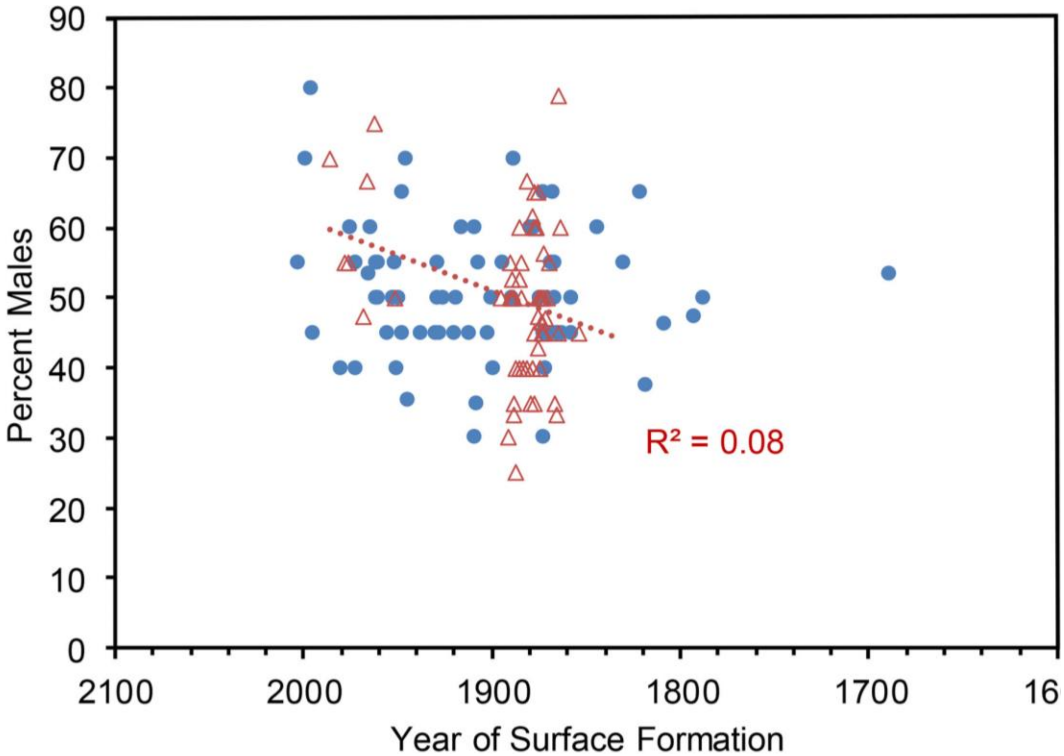

Figure 11. Percent of cottonwoods that are male as a function of surface age at Theodore Roosevelt National Park. Each point represents 5 to 20 trees growing in a roughly even-aged stand. At the North Unit (blue circles) there is no significant relation between percent males and surface age ($p>0.05$). At the South Unit (red triangles) there is a small decrease in percent males with increasing age.

We tested the hypothesis that cottonwoods become established only on new floodplain surfaces at THRO by comparing ages of trees to independently determined estimates of surface age. At 394 randomly selected points on the floodplain of the Little Missouri River in the North Unit (Figure 12; Edmondson et al. 2014), we cored the closest tree (Figure 13) 1.2 m above ground and determined the year of the center ring. We used aerial imagery (photographs and satellite images) captured approximately every ten years beginning in 1939 to obtain an independent estimate of the age of the underlying surface. We mapped the channel in each aerial image (Miller and Friedman 2009), and then identified the most recent image in which the location of a cored tree was mapped as channel. The average of the date of that image and the date of the subsequent image was our estimate of the age of the surface (Figure 12). For the 72 trees on surfaces that were mapped as channel in at least one of the aerial images, the age of the center ring of the tree was an average of 9.7 years younger than the age of the underlying surface from aerial imagery (Figure 14). This is consistent with the hypothesis that trees establish on new surfaces and suggests that there is a lag of about 10 years for a tree to become established on the point bar and grow to coring height of 1.2 m. Occasionally damage from ice or beavers extends this lag for as long as a few decades (Figure 14). Gaps of 8-13 years between images introduced uncertainty in the estimated ages of surfaces (Figure 12), which probably explains the 8 trees that appeared to be about 5 years older than the underlying surface (Figure 14).

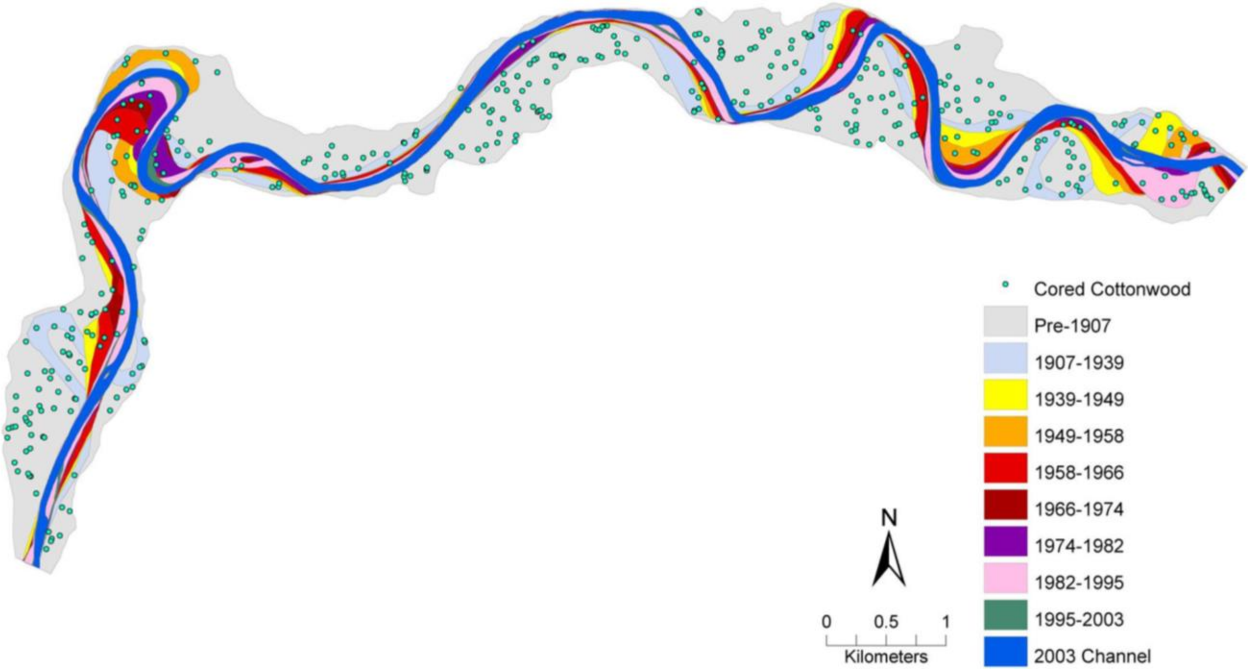

Figure 12. Random cottonwood tree locations along the Little Missouri River in the North Unit of Theodore Roosevelt National Park, ND. Colors are flood plain ages determined using aerial imagery. Figure prepared by Julian Scott.

Figure 13. A plains cottonwood, the increment borer used to collect a core 1 cm in diameter, the core, and a paper straw used to transport the core. Photo by Derek Schook.

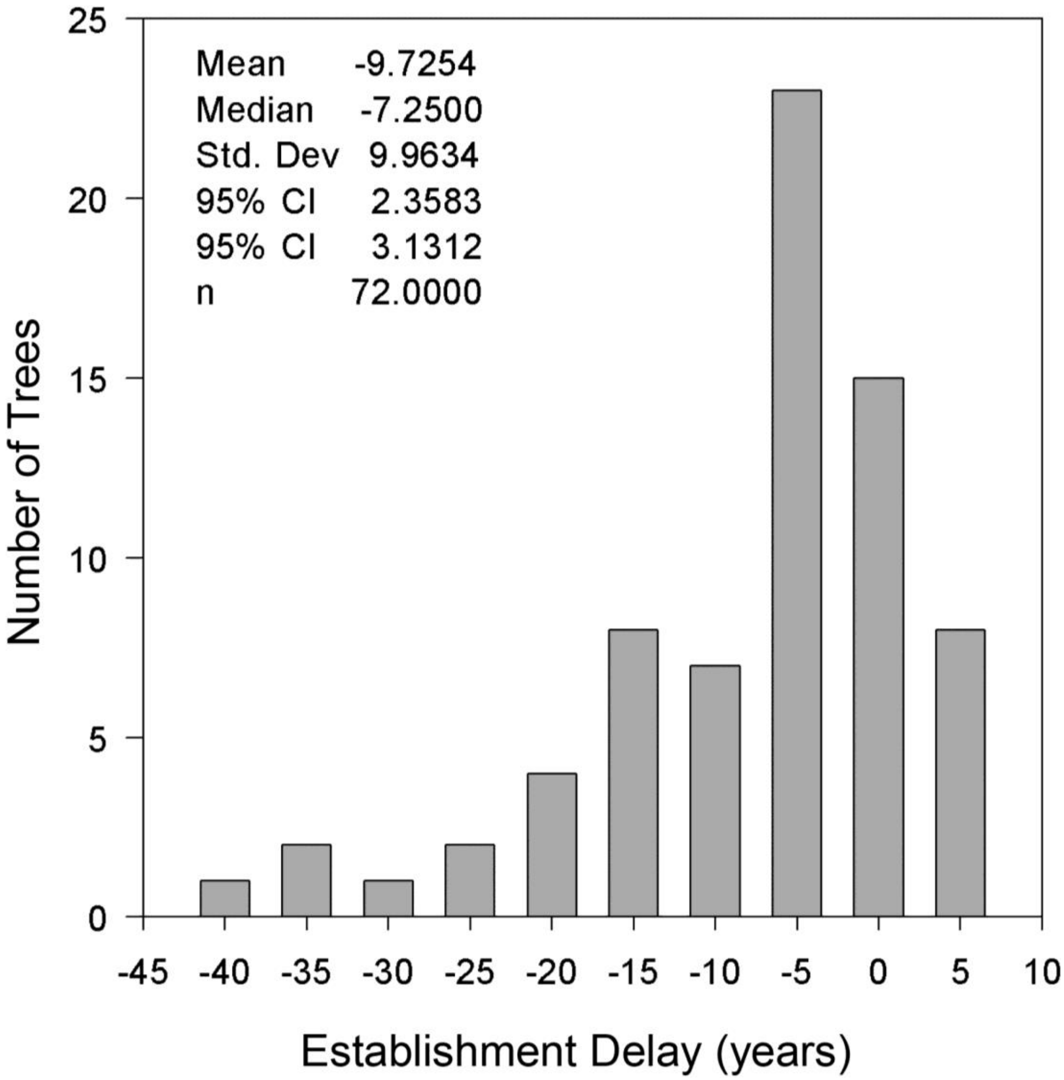

Figure 14. Histogram of the difference between age of tree and age of underlying surface along the Little Missouri River, ND, in the North Unit of Theodore Roosevelt National Park. Negative establishment delay indicates that the center ring of the tree 1.2 m above the ground is younger than the age of the surface estimated from aerial photos.

Because the trees cored at THRO are at randomly selected locations, the ages of the trees are a representative sample of floodplain age, and the relation between forest age and area (Figure 15) provides a record of past rates of channel movement. For example, during the flow record of the stream gage at Watford City (1935-present) the two highest peak instantaneous flows occurred in 1947 and 1950 (Figure 16). Erosion during these floods, and floodplain formation during the drought of the 1950s, have been documented using aerial photography by Miller and Friedman (2009). The cottonwood forest area for the North Unit peaks for trees with center rings around 1960 (Figure 15), and given the establishment delay of roughly 10 years for cottonwood at THRO (Figure 14), this is consistent with floodplain formation during the low flows in the 1950s. Prominent peaks in cottonwood forest area at the North Unit also occur prior to the flow record in 1824-1842 and 1864-1891 (Figure 15). Taking into account cottonwood establishment delay, these dates suggest floodplain formation in 1814-1832 and 1854-1881, two periods that include the most severe droughts in the 1800s (see section on ring width below). Prior flood-related widening for these two establishment bursts cannot be documented because there are no flood records for this area prior to the late 1800s.

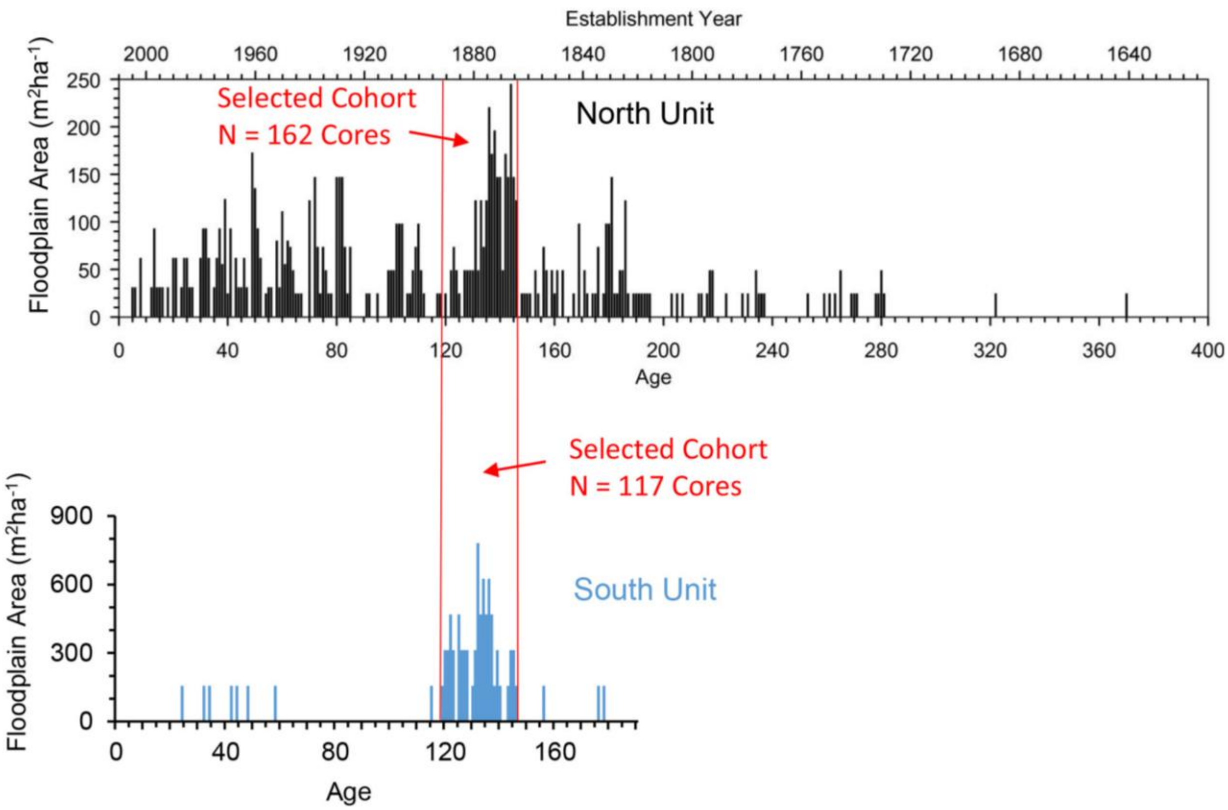

Figure 15. Floodplain area vs. age and establishment year for randomly selected trees along the Little Missouri River in the North and South units of Theodore Roosevelt National Park. The cohort established between 1864 and 1891 (red lines) was used to compare growth at the two units in Figure 23.

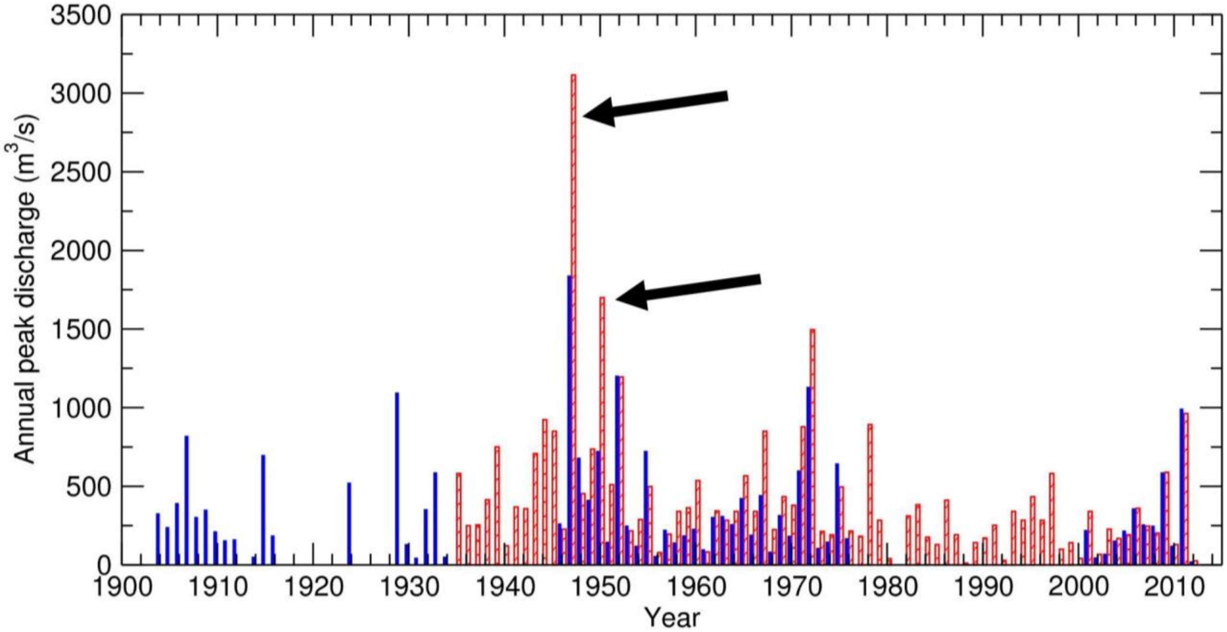

Figure 16. Annual peak instantaneous flow of the Little Missouri River at the North (red) and South (blue) units of Theodore Roosevelt National Park, ND. The two largest floods at the North Unit in 1947 and 1950 are indicated by arrows. Both events were ice related and were much larger at the North than at the South Unit.

If floodplain and forest were created and destroyed at a constant rate and the likelihood of destruction were uniform across the floodplain, then we would expect an exponential relation between age and floodplain area, with older age classes occupying smaller areas (Merigliano et al. 2013). Deviation from an exponential curve in the relation between area and age provides information on the history of flooding and channel change. At the North Unit of THRO, the area-age distribution generally follows the exponential pattern with two important exceptions. The first is the two bursts of establishment we attributed to bursts of channel change in the mid 1800s in the previous paragraph. The second is a decrease in area of forest established since 1960. This recent decrease in rate of forest establishment reflects a decrease in magnitude of ice-jam floods, caused at least in part by increasing winter temperatures (Figure 17, Griffin and Friedman 2017). This decrease in flood magnitude has decreased erosion and channel migration (Miller and Friedman 2009) slowing the rate of new floodplain formation and cottonwood establishment.

At the South Unit the 1864-1891 cohort accounts for 83% percent of forest area (Figure 15), based on establishment years of 65 cottonwood trees cored at randomly selected locations. Taking into account the 10-year establishment delay, this pattern suggests that the only flood large enough to cause widespread channel change and forest establishment at the South Unit occurred before 1854. Otherwise, channel change and cottonwood establishment since 1800 have been limited at the South Unit. One explanation for the more frequent channel change and cottonwood establishment at the North Unit is higher peak flows (Figure 16, Griffin and Friedman 2017), especially in 1947 and 1950, the years of highest peak flows at the North Unit. This is consistent with a tendency for ice jamming to become more severe in the downstream direction along the Little Missouri River (Griffin and Friedman 2017). Lower flood peaks are not sufficient to explain the greatly reduced channel migration at the South Unit, however, given that the highest flow in the record from the South Unit would have been the second highest flow at the North Unit (Figure 16). Similarly, the slightly higher floodplain gradient at the North Unit (Table 1) is not sufficient to explain its much greater channel mobility. Other possible explanations for reduced channel mobility at the South Unit include bedrock constraint, confinement by the railroad and highway crossings just upstream of the South Unit, and larger sediment particle size.

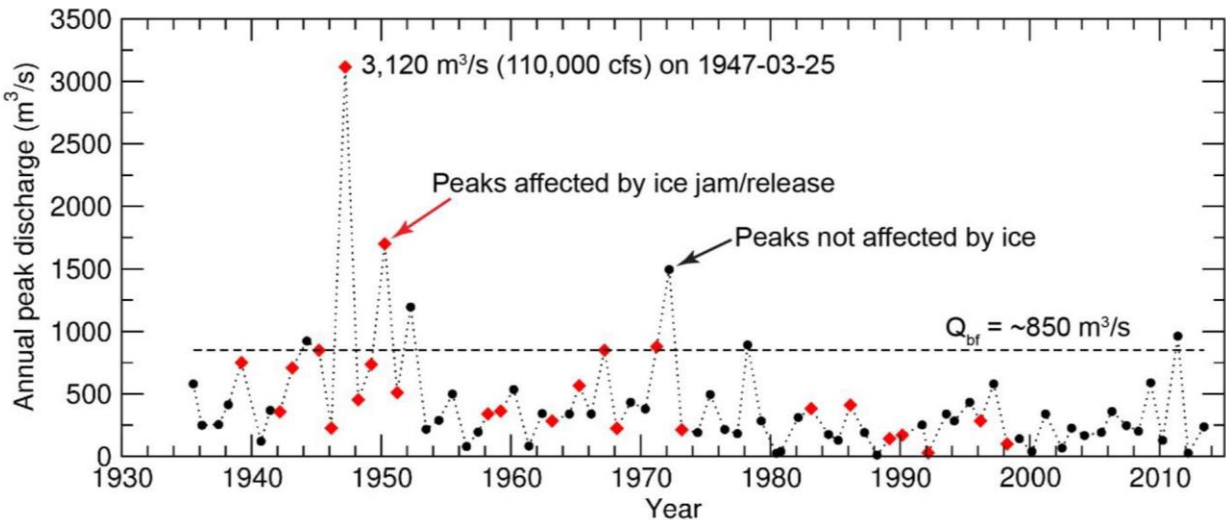

Figure 17. Record of annual peak discharge (by Water Year) for the gage at the North Unit of Theodore Roosevelt National Park, Little Missouri River near Watford City, ND, 1935 - 2013. Peaks affected by ice are shown in red while peaks not affected by ice are shown in black (Griffin and Friedman 2017).

In summary, cottonwoods become established during periods of relatively low flows following erosive floods. In other words, cottonwood establishment at THRO is related to low flows at the scale of years to decades, but to high flows at longer time scales (Friedman and Lee 2002). From the point of view of water management, it is important to stress that erosion during large floods is essential to maintenance of cottonwood reproduction over the long term because this flood erosion creates space for formation of new floodplain surfaces necessary for cottonwood seedling establishment. Decreased snowmelt flood peaks at THRO related to recent winter warming have moderately reduced the rate of cottonwood reproduction at the North Unit (Figure 15). On many other rivers in the northern Great Plains, a more severe reduction in peak flows has resulted from construction of reservoirs. For example, construction of reservoirs along the Missouri River, the trunk stream of the northern Great Plains, has greatly reduced peak flows, channel migration and cottonwood establishment (Johnson et al. 2012).

Table 1. North and South Unit valley floor and channel geomorphic parameters.

Parameter	South Unit	North Unit
Valley centerline length (m)	14,863	13,286
Average valley floor width (m)	574.0	758.6
Average floodplain slope down-valley (m)	0.00082	0.00092
River centerline length (m)	16,655	17,845
Average channel sinuosity	1.121	1.343
Average channel slope	0.00046	0.00048
Average water-surface width (m)	63.4	78.5
Average estimated bankfull channel width (m)	96.6	108.6

Cottonwood Growth is Strongly Affected by Decreases in Flow

The climate of western North Dakota is so dry that growth of cottonwood trees is limited by water availability even on a floodplain. Cottonwood ring width at THRO is strongly positively correlated with flow and precipitation and weakly negatively correlated with temperature (Figure 18, Edmondson et al. 2014, Meko et al. 2015). In other words, higher flows and precipitation increase growth, while lower flows and hotter, drier conditions decrease growth. This fact is the basis of reconstructions of drought and flow (Edmondson et al. 2014, Meko et al. 2015, Schook et al. 2016) and has important implications for management of cottonwood at THRO.

The relation between river flow and growth is non-linear. The effect on growth of a given decline in flow becomes stronger with decreasing flow. In fact growth is less strongly related to flow than to the logarithm of flow. (Figure 19, Meko et al. 2015). This means that low-flow events have a disproportionately large effect on tree growth, and that ring widths record droughts (Figure 20) more precisely than high flow periods. The severity and duration of drought necessary to kill cottonwoods at THRO is not known and is an important area for future research. Nonetheless, it is already known that if drought effects become severe enough, cottonwood trees will die. For example, extreme drought in the Great Plains in the 1930s caused widespread mortality of riparian cottonwoods (Albertson and Weaver 1945). At THRO ring widths indicate that the worst drought of the last 300 years occurred in 1816-1823 (Figure 21, Schook et al. 2016). This drought also corresponds to a break in the age distribution of the forest: a much larger proportion of existing trees were established in the decades after this drought than in the decades before it (Figure 15), suggesting that many trees were killed by the drought. For the same reason the number of cottonwood stems per hectare is lower for stands established before the drought than for stands established after it (Figure 10). High tree mortality during this drought is consistent with the subsequent temporary extreme increase in growth of surviving trees at the North Unit in the 1820s (Figure 21) partly caused by a release from competition for water, light and nutrients (Scott et al 1999, Schook et al. 2016). In other words cottonwoods that survived the drought grew faster because many of their neighbors were killed.

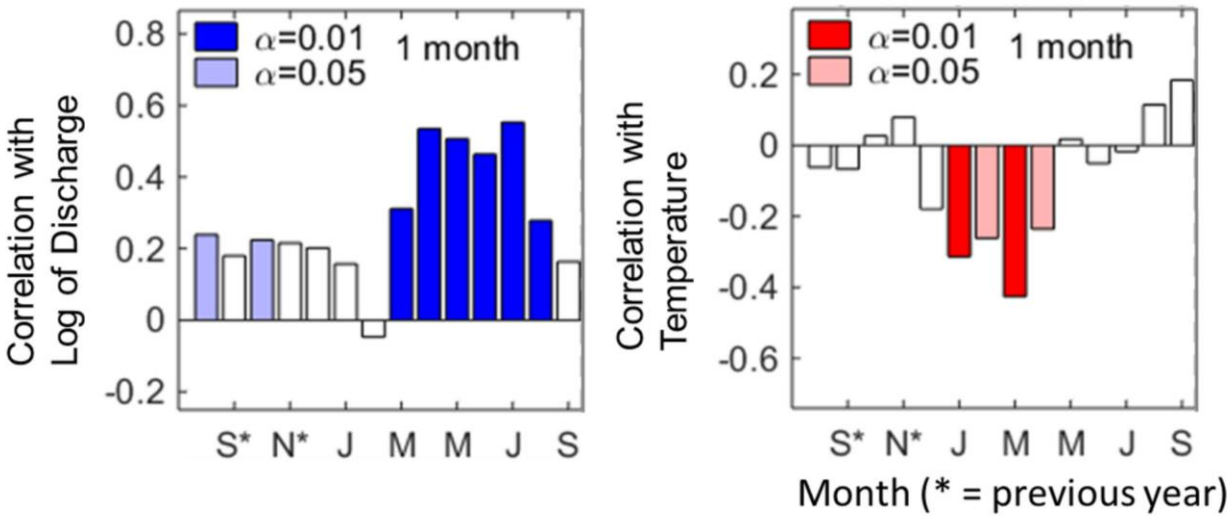

Figure 18. Left, correlation between annual cottonwood growth and log of monthly mean discharge at the North Unit of Theodore Roosevelt National Park. Right, partial correlation between annual growth and monthly maximum temperature after removal of the effect of discharge. Period of analysis is 1931-2010. Dark blue or red bars are highly significant ($p<0.01$), light blue or red bars are significant ($p<0.05$), and clear bars are insignificant ($p>0.05$). Annual growth is for trees aged 5-35 years at the North Unit of Theodore Roosevelt National Park from Meko et al. (2015). Flow data are for the Little Missouri River near Watford City (gage 06337000) supplemented before 1935 by correlation with data from the Little Missouri River at Medora (gage 06336000). Temperature data are from Prism (Daly et al. 2008). Output from SEASCORR (Meko et al. 2011).

A decrease in tree growth since about 1976 (Figure 21) corresponds to a decrease in flow over the same period (Figure 22). This decrease in flow coincided with increases in temperature but precipitation did not change. Griffin and Friedman (2017) concluded that the decrease in flow was mostly caused by the increase in evapotranspiration related to higher temperature. Future increases in temperature related to global climate change could cause future decreases in flow and cottonwood growth; however, effects of global climate change on future precipitation that could also affect flow in this region are uncertain (Kunkel et al., 2013).

Reconstructions of flows at THRO using cottonwood tree rings (Figure 21) provide an important long-term perspective not available from the relatively short flow record, which extends back to 1935 at the North Unit (Little Missouri River near Watford City, ND, 06337000) and to 1903 with gaps at the South Unit (Little Missouri River at Medora, ND, 06336000). For example, although there has been a moderate decrease in flow and cottonwood growth at the Little Missouri River over the period of flow record, at a longer time scale the 1900s were relatively wet compared to the 1700s and 1800s (Meko et al. 2015). Two droughts in the 1800s, 1816-1823 and 1859-1865, were more severe than any droughts recorded in the 1900s. Occurrence of these 1800s droughts are confirmed by Lakota winter counts (Therrell and Trotter 2011) and other tree-ring studies from the region (Cook et al., 2008).

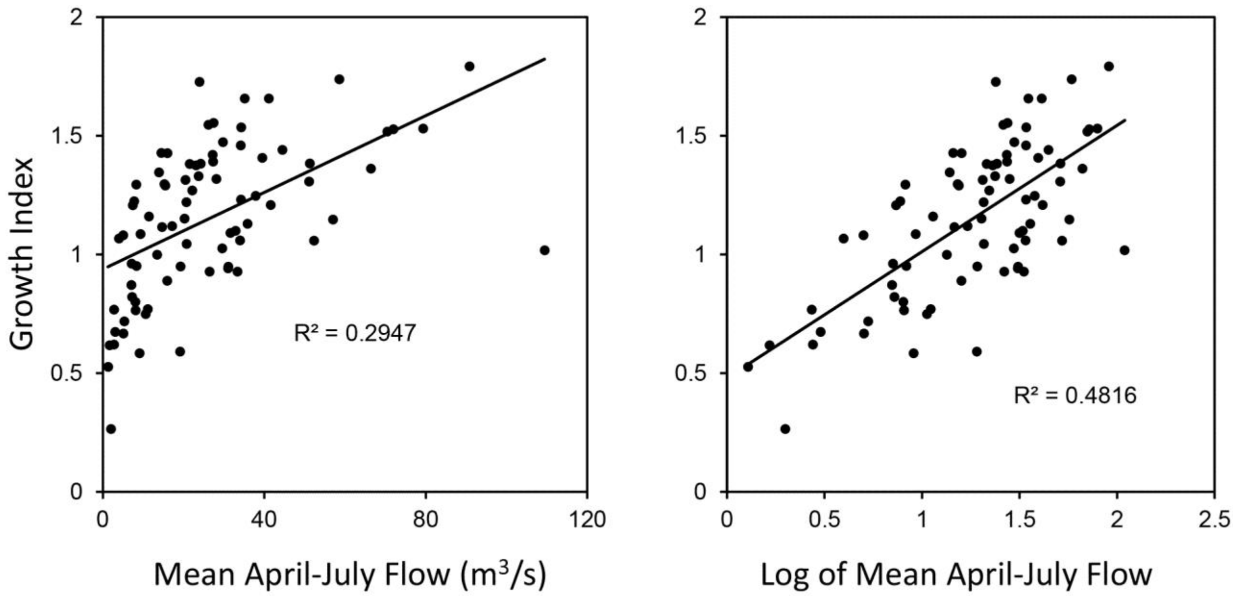

Figure 19. Cottonwood growth as a function of (left) annual mean April-July flow, and (right) log of annual mean April-July flow (1931-2010). Cottonwood growth is an index of the average growth corrected for age of trees aged 5-35 years old at the North Unit of Theodore Roosevelt National Park (from Meko et al. 2015). Flow data are for the Little Missouri River near Watford City (gage 06337000) supplemented before 1935 by correlation with data from the Little Missouri River at Medora (gage 06336000).

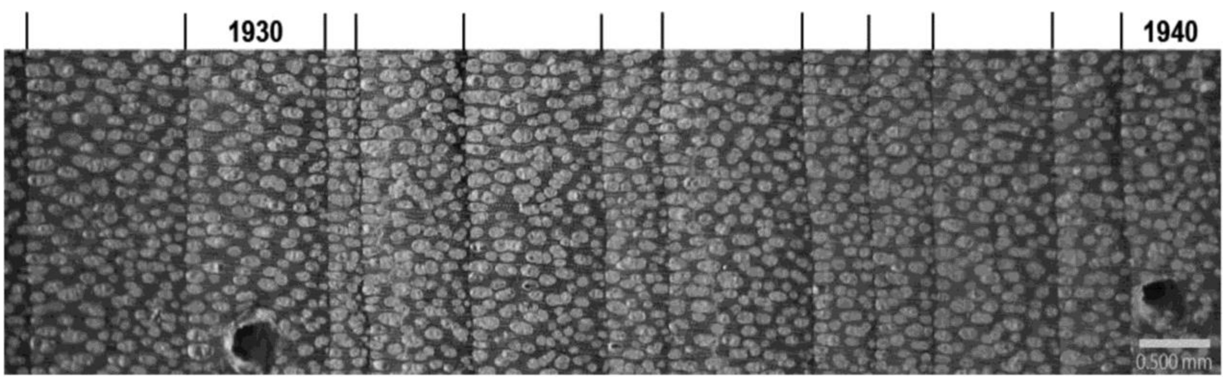

Figure 20. Photomicrograph of annual rings in a core of plains cottonwood from the flood plain of the Little Missouri River in the North Unit of Theodore Roosevelt National Park, ND. Narrow rings in 1931 and 1934 correspond to drought years during the Dust Bowl of the 1930s. Photo by Jesse Edmondson (Reprinted from Edmondson et al, 2014).

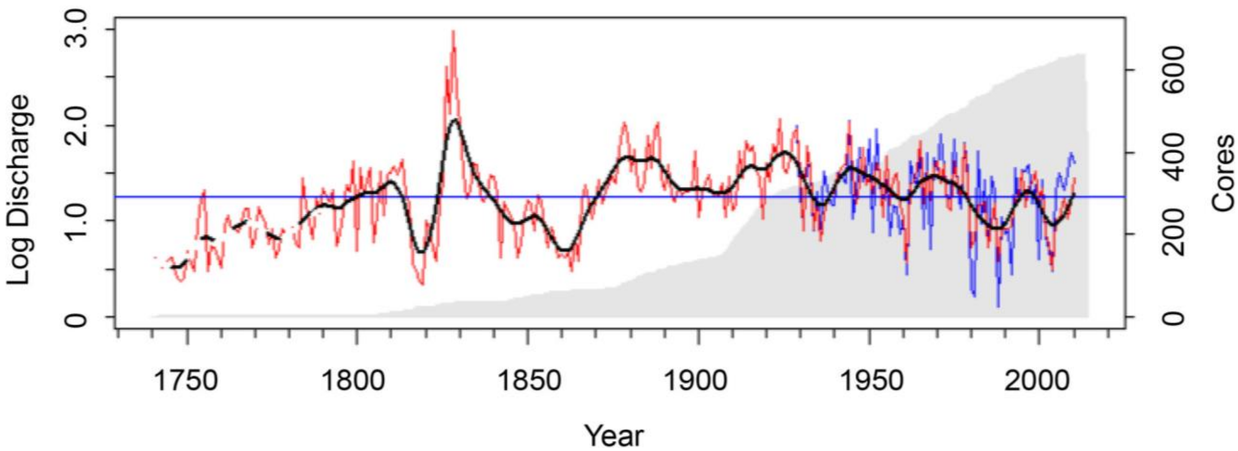

Figure 21. Reconstruction of log-transformed April-July Flow of the Little Missouri River near Watford City ND, gage 06337000, in the North Unit of Theodore Roosevelt National Park. This reconstruction is based on cores of plains cottonwood from the North Unit and from the lower Powder River near Moorhead, MT. Blue line is measured log of discharge, red line is reconstructed log of discharge, and black line is 15-yr smoothing spline. Spline is dashed where confidence in the reconstruction is low because of small sample size. Shaded area is the number of cores in each year. From Schook et al. 2016.

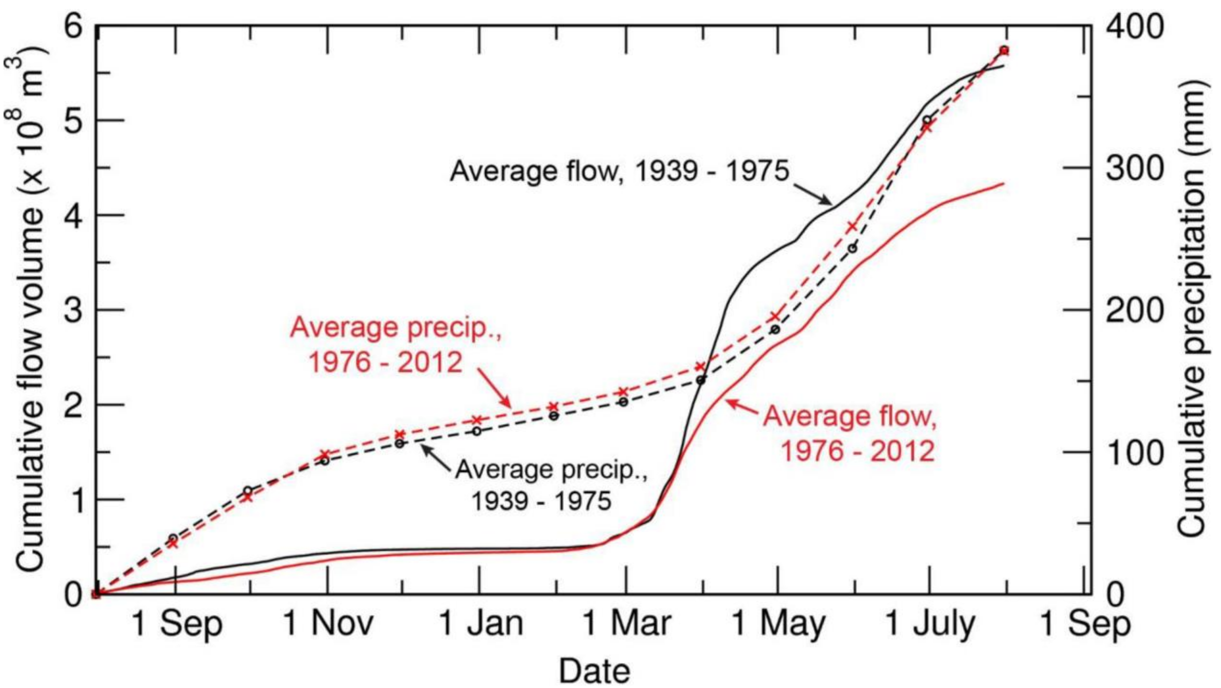

Figure 22. Average cumulative flow volume, Little Missouri River near Watford City, North Dakota (solid lines) and basin-wide average precipitation (dashed lines) for 1939-1975 (black) and 1976-2012 (red). Reprinted from Griffin and Friedman (2017).

The floodplain environment at THRO becomes progressively drier over the growing season. Monthly mean flow peaks in March or April, precipitation peaks in June, and temperature peaks in July and August (Figure 2). As a result most cottonwood growth occurs early in the growing season. The months in which flow and precipitation are most highly correlated with annual tree growth are April-July (Figure 18) Later months show a relatively weak relation between flow and growth and this effect is not felt until the following year (Figure 18). This relation is consistent with the observation that plains cottonwood twig growth ends in June or July (Friedman et al. 2011). Therefore, flow regulation that delayed flows until after July could decrease cottonwood growth even if mean annual flow did not change (Schook et al. 2016).

Because growth and survival of cottonwood trees are strongly decreased by extreme low flows, any management activity that decreases low flows could strongly reduce growth or kill trees. Such activities include diversions of surface flow and groundwater pumping from the alluvial aquifer, which can decrease both surface flow and the floodplain water table. Surface-flow diversions are less damaging to trees if carried out during the spring when flows are relatively high. Much of the groundwater pumping in the Little Missouri River Basin is from bedrock aquifers beneath the alluvial aquifer (Griffin and Friedman 2017). It is unknown to what degree, if any, pumping in these bedrock aquifers affects flow in the river or water tables on the floodplain.

Differences in Growth between the North and South Units

To assess effects of management and environment at THRO on growth of cottonwoods we compared average growth rates at the North and South Units. To control for the effect of age on growth (Meko et al. 2015) we limited our tree sample at both units to trees established between 1864 and 1891: 162 cores from the North Unit and 117 cores at the South Unit (Figure 15). We then calculated the average growth rate at each unit in each year and determined the ratio of average growth at the South Unit divided by average growth at the North Unit for each year. The ratio is close to 1 most of the time indicating that growth rate is similar at the two sites (Figure 23). Positive excursions of the ratio in 1908-1909 and 1946-1947 indicate that some factor was strongly depressing growth at the North Unit in these years, possibly a local outbreak of the cottonwood leaf beetle (*Chrysomela scripta*, Andersen 2016) or leaf rust (*Melampsora medusae*). Decline of the ratio during the two worst droughts of the 1900s, 1931-1938 and 1988-1992, indicates that the trees are more susceptible to drought at the South Unit than at the North Unit. The higher susceptibility to drought at the South Unit could be related to higher temperatures or to differences in local groundwater availability in the alluvial aquifer. Average growth at the South Unit has not recovered following the drought that ended in 1992, which may reflect effects of herbicide application at the South Unit.

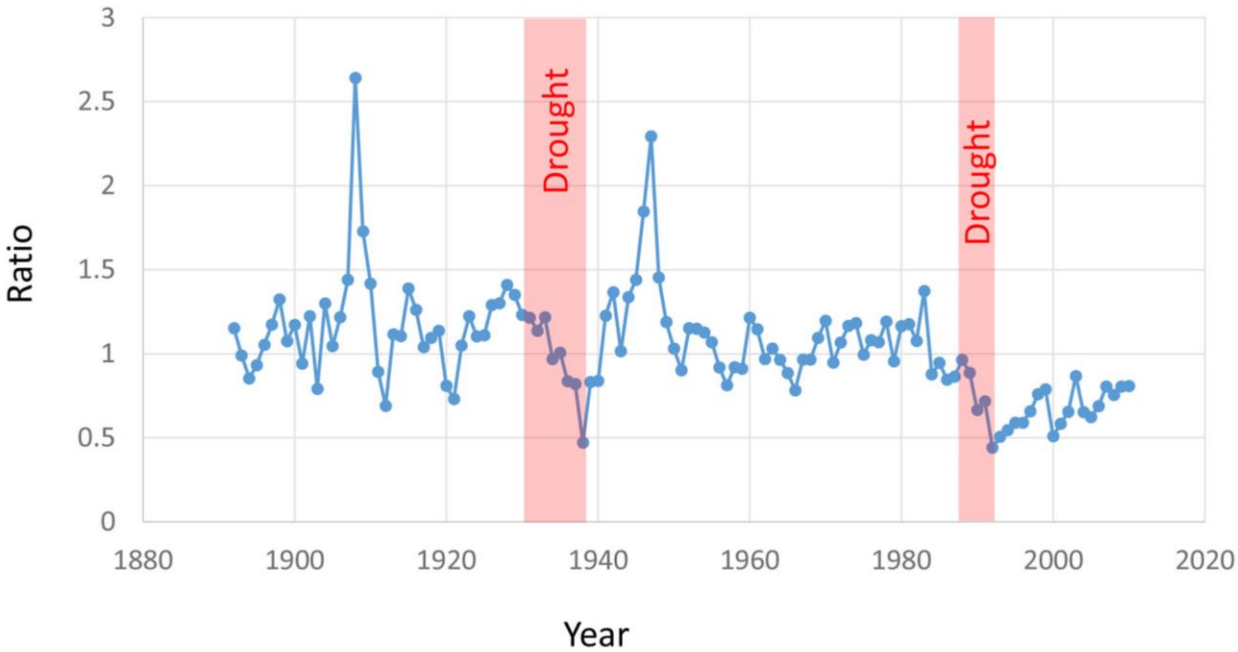

Figure 23. Mean Raw Cottonwood Growth Ratio, South Unit Divided by North Unit, for Trees Established Between 1864 and 1891, Theodore Roosevelt National Park, ND. The two strongest droughts in the twentieth century are highlighted in red.

Effects of Herbicide on Cottonwood Survival and Reproduction

Beginning in 1993 THRO has controlled the invasive herb leafy spurge (*Euphorbia esula*) in the riparian zone using the herbicide Plateau® applied by helicopter, almost entirely in the South Unit. According to the herbicide label (http://www.cdms.net/ldat/ld2LP015.pdf accessed November 11, 2016), the recommended application rate for leafy spurge is 8-12 oz. per acre, but 12 oz. per acre causes injury or death to both cottonwood and green ash, the two most abundant broadleaf trees on the floodplain of the Little Missouri River in THRO. During tree coring in 2012, we observed large areas of cottonwood mortality (Figure 24) and prepared a rough map of areas where cottonwoods are mostly dead (Figure 25). These areas of cottonwood damage, roughly one quarter of the cottonwood forest at the South Unit, coincide with locations that have been sprayed multiple times to control leafy spurge (Figure 25). Cores of 25 dead trees indicated that cottonwood mortality peaked in 2005-2007, the years of most widespread herbicide application (Figure 26). Historic aerial imagery of the location shown in Figure 24 (viewed in Google Earth, accessed November 10, 2016) indicates that the dead trees in Figure 24 appeared healthy as late as July 29, 2005. Precipitation and flow were moderate in 2005-2007 (Figure 26) suggesting that mortality of trees was not primarily caused by drought, although the earlier minor drought from 2002-2004 may have moderately stressed the trees. There are small areas that have been sprayed 3 or more times, yet have healthy trees (Figure 25), suggesting that variation in timing or intensity of spraying may influence tree survival. In recent years THRO has attempted to reduce impact of herbicide on cottonwood by reducing areas sprayed in the floodplain (Figure 26) and by spraying later in the season, when cottonwood leaves have started to turn yellow. These efforts appear to have reduced mortality of adult trees (Figure 26).

Figure 24. Plains cottonwood killed and damaged by helicopter application of herbicide at the South Unit of THRO. Photo by Jonathan Friedman, April 20, 2012. Photo was taken before cottonwood leaf buds opened for the year. Trees with white trunks have lost their bark and are dead. Some of the trees with black trunks are still alive and were producing flowers at the time of the photo. Understory green trees are juniper. Photo view is looking west from latitude 46.9675˚, longitude -103.4938˚.

Herbicide application may also be killing seedlings of cottonwood, which become established near the channel on point bars, and are generally inconspicuous. The slow rate of formation of point bars is one of the factors limiting cottonwood reproduction in the South Unit (Figure 15). Herbicide application on point bars would further limit that reproduction, but assessing this possibility would require additional data on precise locations of cottonwood seedlings. Other factors could limit cottonwood reproduction at the South Unit. Ice jams can remove cottonwood seedlings in some years, but are generally more severe at the North Unit, where cottonwood reproduction is abundant, than in the South Unit, where reproduction is scarce. Another factor that could explain reduced reproduction of cottonwood at the South Unit relative to the North Unit is differences in intensity of grazing by elk and bison. This hypothesis is consistent with occurrence of elk in the South Unit but not the North Unit, but there have been no studies of grazing effects on cottonwood establishment at THRO.

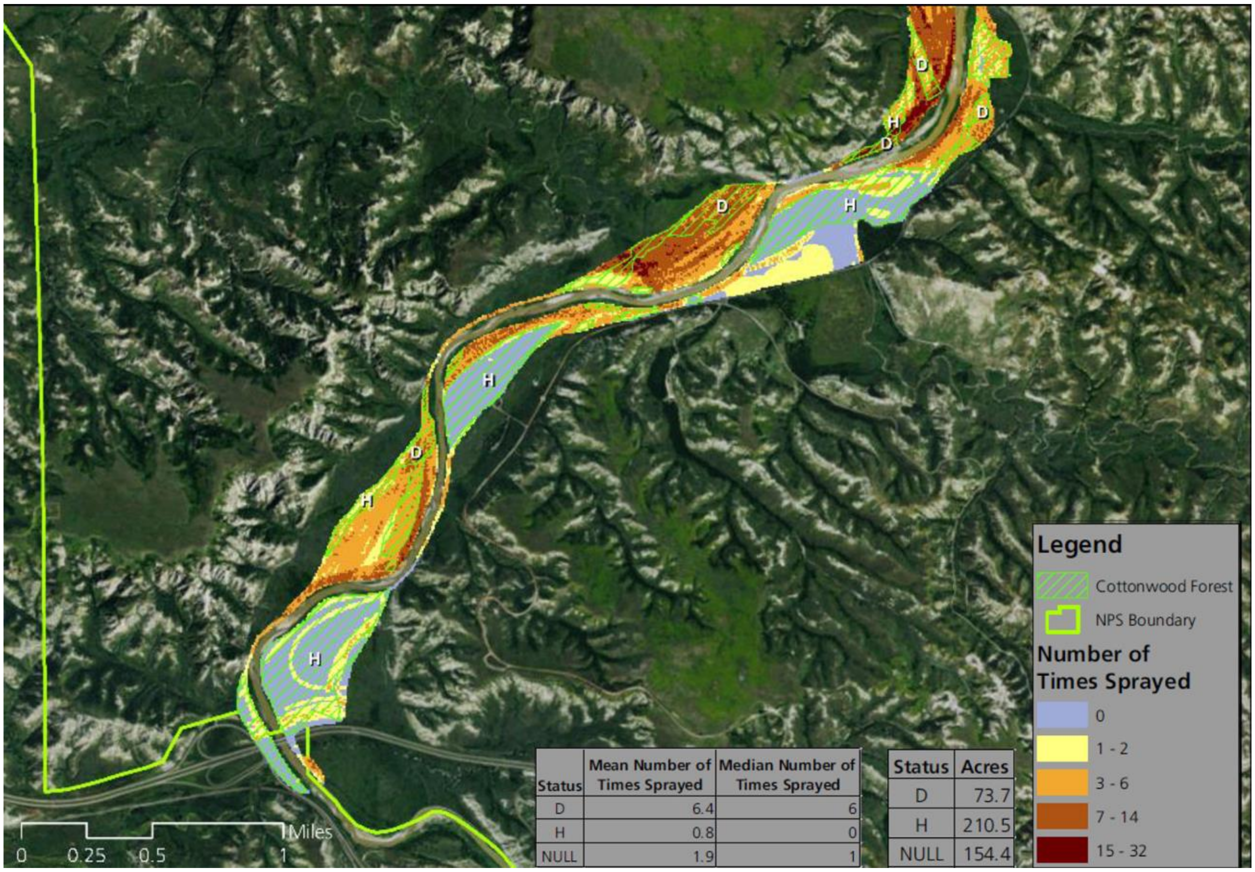

Figure 25. Cottonwood forest status overlain on the number of times sprayed by helicopter application of herbicide. Cottonwood forest is shown by green hatching. D indicates most trees are dead or mostly dead. H indicates most trees are mostly alive. Areas of forest not mapped as D or H are categorized as NULL. Prepared by Jeremy Cantor, NPS.

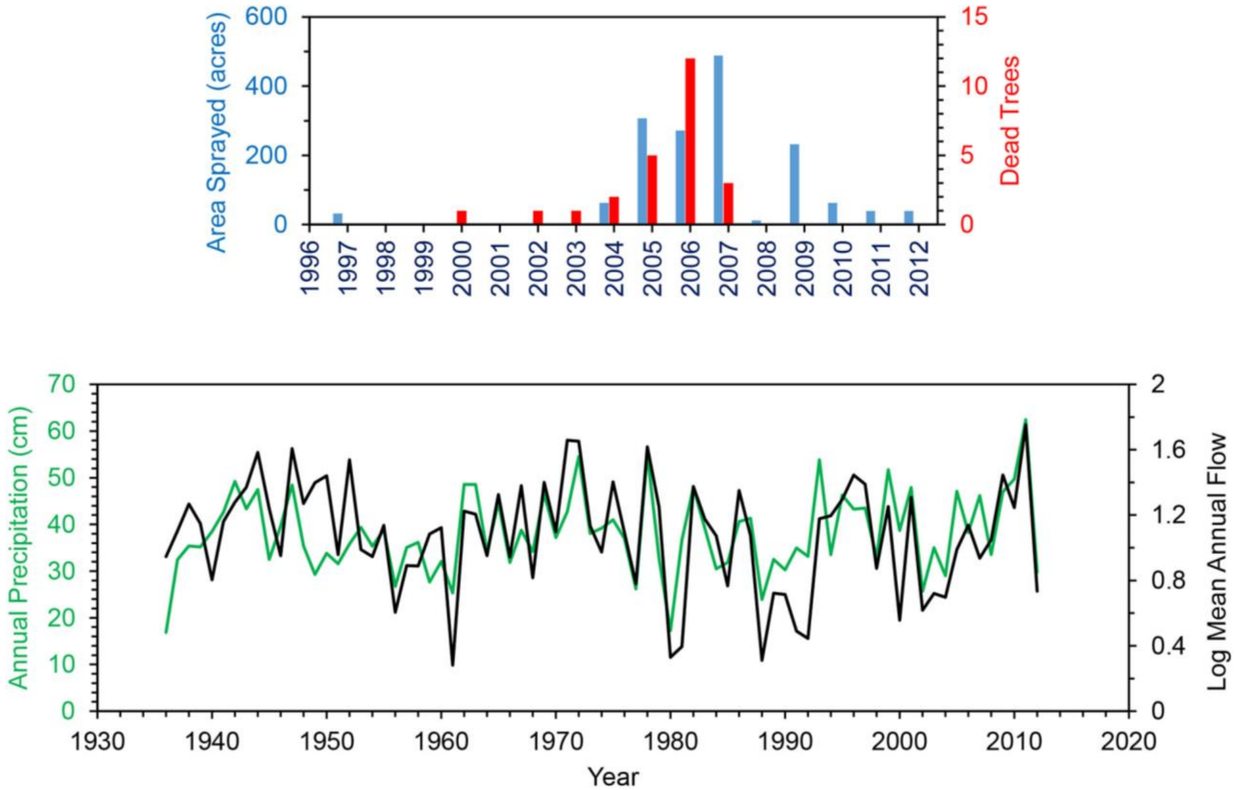

Figure 26. Top, in blue, total area of the flood plain sprayed each year by helicopter application of herbicide, South Unit of Theodore Roosevelt National Park, ND (Data analyzed by Jeremy Cantor, NPS); and in red, year of death (last year of growth) of 25 dead trees cored in the South Unit of Theodore Roosevelt National Park, ND. Bottom, in green, basin-averaged annual precipitation (August-July) from Griffin and Friedman (2016); and in black, log of mean annual discharge (August-July) at Watford City, ND. Flow and precipitation data from Medora, ND were not used because of incomplete data.

Areas for Future Research

Given the observations of increasing temperatures and decreasing flows in the Little Missouri River, research is needed to quantify flows necessary to prevent cottonwood mortality on different parts of the floodplain. Developing an understanding of the relation between streamflow, precipitation and soil moisture across the floodplain would be needed to answer this question. This research could take advantage of recently acquired LiDAR topography that now makes it possible to relate tree growth and survival to microtopography. Cores of dead trees in the North Unit can be used to relate mortality to specific drought events.

As demand for water increases in the region, it becomes increasingly important to understand the relation between groundwater pumping from multiple aquifers and surface flow in the Little Missouri River.

To better understand how herbicide application to control leafy spurge is affecting cottonwood trees, detailed maps of both seedlings and dead and dying adults need to be prepared. These maps should be compared to location, dosage, years and seasonal timing of herbicide application to help identify weed control techniques that are most consistent with long-term maintenance of the forest and to help managers balance the benefits of weed control with the costs of damage to cottonwood forests.

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